Physics-Based Impact Risk Modeling

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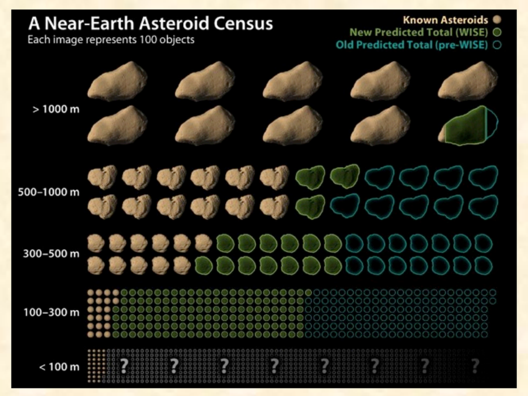
OVERVIEW & OBJECTIVES

The Engineering Risk Assessment (ERA) team is developing a physics-based, probabilistic risk model for assessing potentially hazardous asteroid (PHA) impact threats. The model integrates probabilistic sampling of uncertain asteroid parameters with physics-based analyses of key entry, breakup, and airburst processes to estimate expected damage areas and casualties from various classes of PHAs. The model is used to perform sensitivity studies, bound potential consequences of impact scenarios with uncertain characteristics, and investigate the implications of specific impact factors and cases. These results provide insight into which parameters most significantly drive the risks, the relative importance of characterizing or measuring those parameters to varying degrees of accuracy, and what physical models are most important to refine in order to meaningfully evaluate risk levels. This work is part of the NASA Ames Research Center (ARC) Planetary Defense Integrated Product Team (PD IPT) initiative to develop predictive impact risk assessment tools that will support mitigation strategy planning and potential threat response decisions.

INPUTS & DATA SOURCES

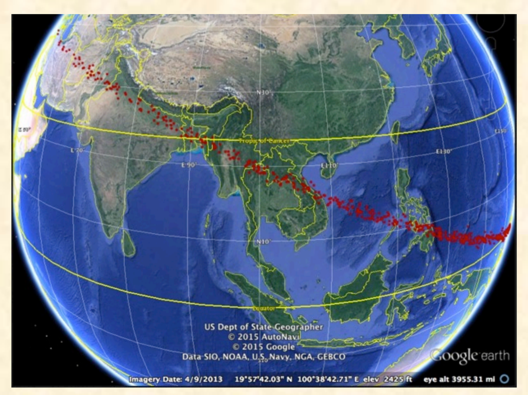
Asteroid Characterization Data

Parameter ranges and frequencies for various classes of PHAs [1,2]



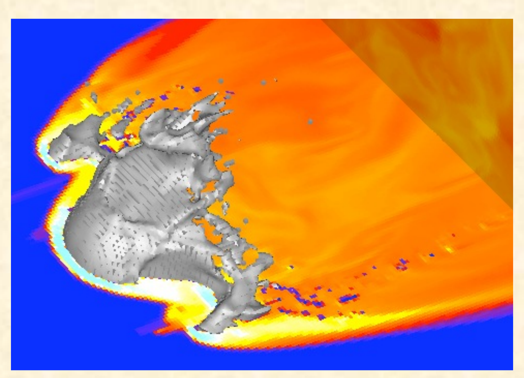
PHA Tracking & Observational Data

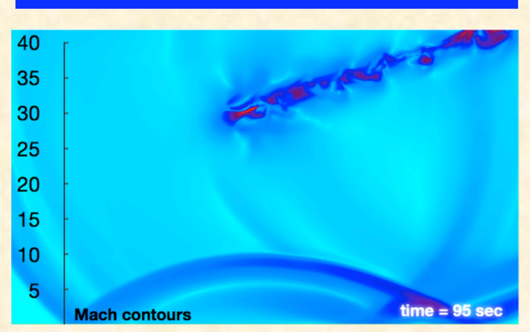
Predicted impact swaths and entry velocity vectors from orbital trajectory tracking [3].



High-Fidelity Simulations

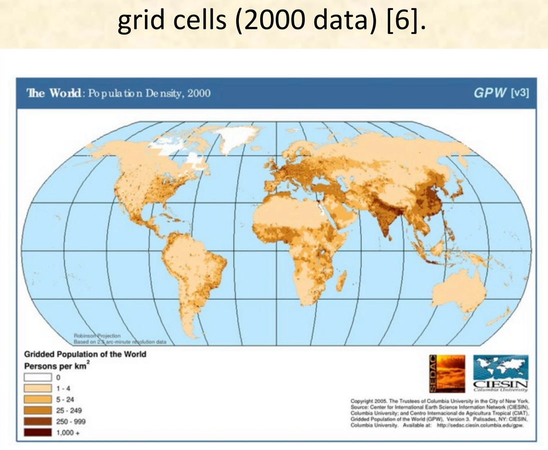
Entry, breakup, airburst, energy deposition, blast propagation, ground damage, tsunami generation [4,5]





SEDAC Gridded Population Data

Population counts within 2.5-arcminute grid cells (2000 data) [6].



PROBABILISTIC SIMULATION

- Dynamic Monte Carlo sampling of uncertain asteroid and impact parameters to generate probabilistic sets of specific strike scenarios.
- Parameters can be fixed or distributed, with ranges set directly or estimated from observational data.
- GUI applet efficiently generates analysis cases for a wide range of parameter spaces and applications.

ENTRY & BREAKUP

Flight Integration
- Numerical integration of equations of motion and ablation to estimate energy deposition during atmospheric entry [7].

Fragmentation & Burst
- Breakup begins when aerodynamic ram pressure at stagnation point exceeds asteroid material strength.
- "Pancake" deformation approach used to model breakup process [7].
- Other progressive and intermediate fragmentation models are currently being implemented [8].

Airburst Altitude & Energy
- Altitude at which meteoroid's kinetic energy (KE) is decreased by half and the remainder is converted into a blast wave.
- If meteoroid reaches ground, impact is treated as an airburst at 0 altitude with remaining KE.

GROUND DAMAGE AREAS

Blast Overpressure
- Threshold: peak overpressure ≥ 4 psi.
- Damage area based on spherical blast propagation formulas for nuclear detonations [9].
- Elliptical damage shape and orientation adjusted based on entry angle and direction (azimuth angle).

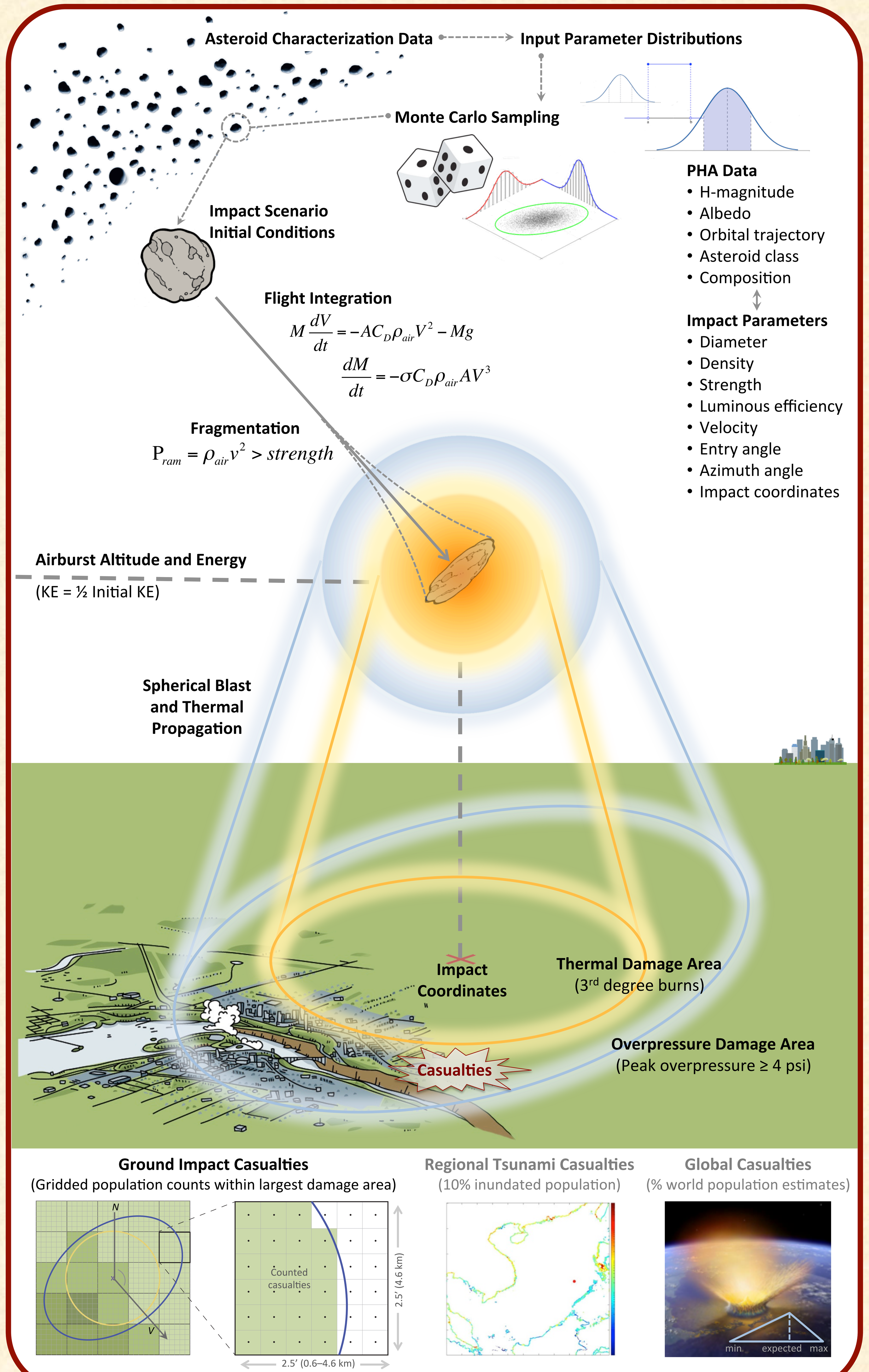
Thermal Radiation
- Threshold: 3rd degree burns.
- Circular damage area based on burst height, energy, and luminous efficiency estimates [10].

CASUALTY ESTIMATES

Ground Impact Casualties
- Gridded population data is used to compute casualties within the largest damage area around specific impact coordinates.
- Population grid cells are divided into user-specified number of sub-cells to scale casualties included from damage boundary cells.

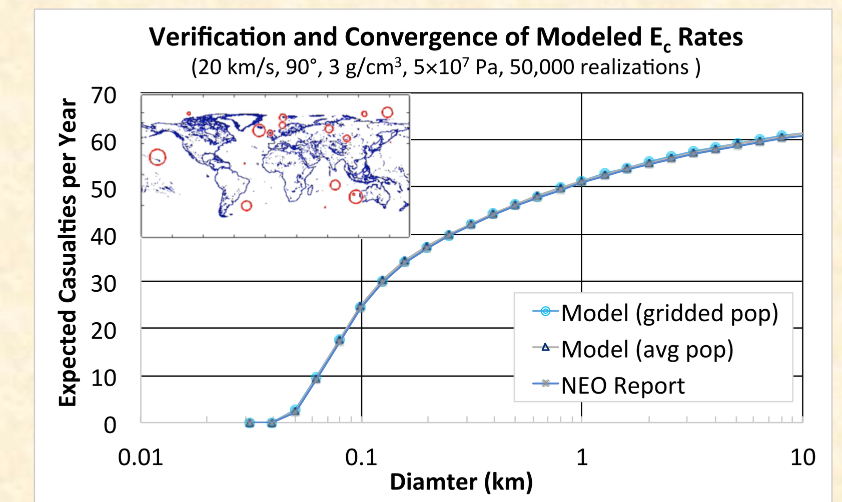
Preliminary Regional Tsunami Inundation
- Estimates inland inundation distance for select strikes based on impact energy and ocean depth [11].
- Assumes 10% of population within inundated areas (over a given threshold distance) are killed [12].

Preliminary Global Climactic Effects
- Estimates percentage world population killed by climactic effects of large impacts ($E > 4 \times 10^4$ MT).
- Samples from triangular distribution of min, nominal, and max percentages based on impact energy [12].

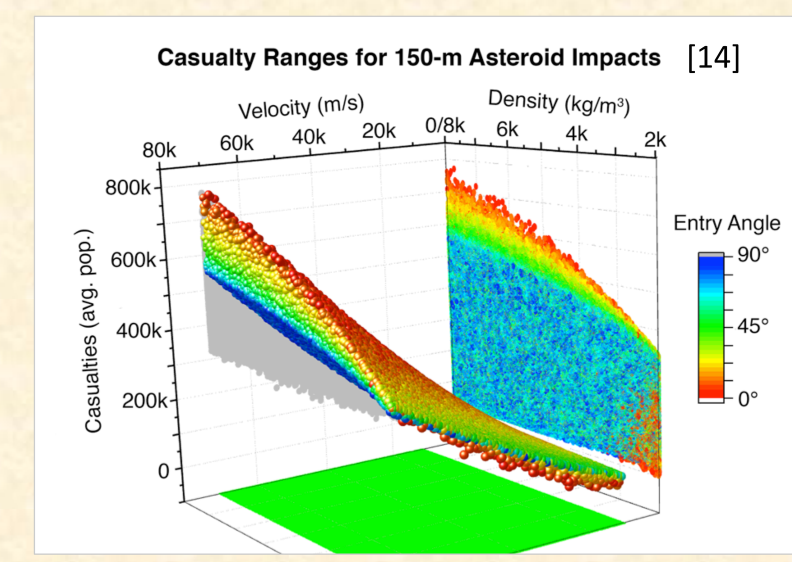


RESULTS & APPLICATIONS

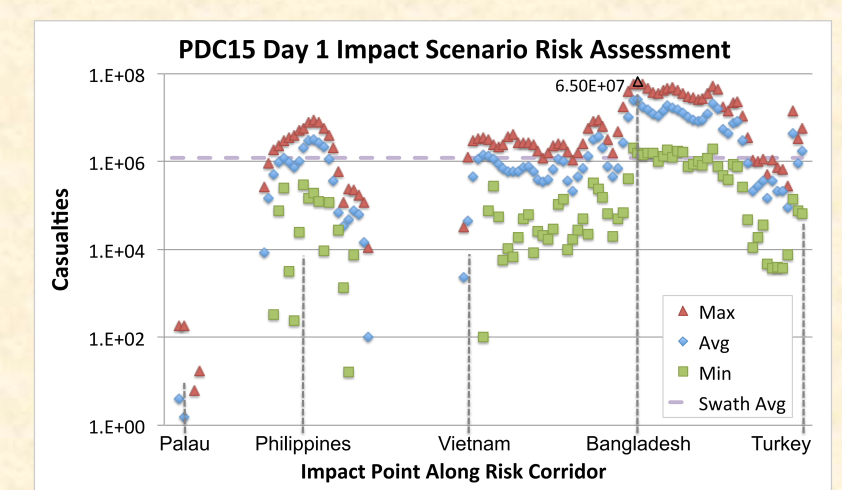
Dynamic risk modeling framework can be used for a range of asteroid impact studies and applications to estimate potential risk levels, identify risk-driving factors, generate meaningful decision support metrics, and provide insight into what PHA characterization research, observational measurements, and mitigation strategies are likely to be most effective.



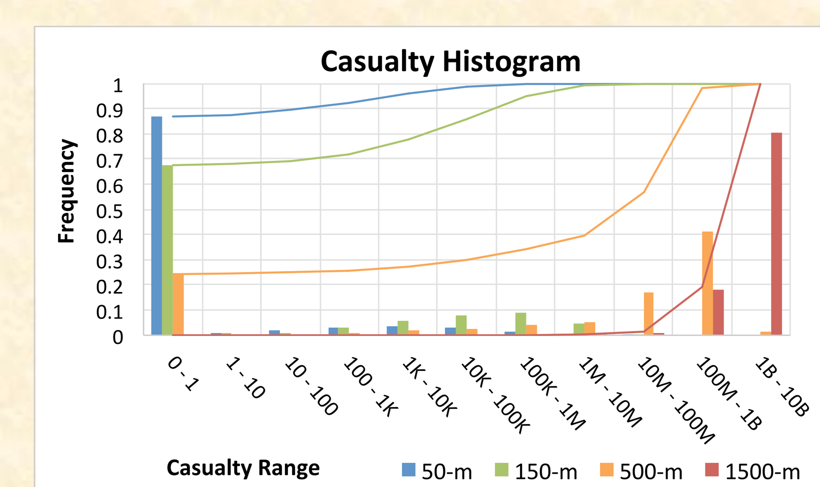
Expected Casualty (E_c) Rates
- Casualties for each impact realization scaled by estimated frequencies per year of that size class.
- Reproduced Stokes et al. [12] results using average world population density for initial model validation.
- Demonstrated convergence of location-specific casualty results with average population results over large number of realizations [13].



Sensitivity Studies
- Investigate effects of parameter variations on damage area and casualty results.
- Determine risk-driving parameters.
- Provide insight into which asteroid characteristics and observational measurements are most important.
- Prioritize refinement of risk-driving assumptions.
- Identify which impact processed should be modeled at higher fidelity.



PHA Risk Corridor Assessments
- Provide damage area and casualty estimates for impacts along risk corridors predicted by PHA trajectory tracking.
- Bound risk estimates based on uncertainties in PHA observational measurements, and their correlation to impact analysis parameters.
- Modeled the 2015 Planetary Defense Conference hypothetical impact drill [3].



Decision Support Metrics
- Produce actionable information to enable risk-informed decisions.
- Inform future mitigation research, development, and capabilities to efficiently reduce risk.
- Identify asteroid sizes and classes warrant tracking or advanced mitigation.
- Guide appropriate levels of mitigation given predicted damage severities and probabilities.

ACKNOWLEDGEMENTS & REFERENCES

[1] Characterization data: Stuart & Binzel, 2004, Icarus 170:295, provided by J. Dotson, NASA ARC. [2] Image: NASA Wide-field Infrared Survey Explorer (WISE) Near-Earth Asteroid Census. [3] P. Chodas, NASA Jet Propulsion Laboratory, NEO Office, 2015 Planetary Defense Conference hypothetical impact exercise. [4] D. Robertson, current workshop poster: Hydrocode Simulation of Mechanical Airburst. [5] M. Aftosmis, NASA ARC. [6] NASA Socioeconomic Data and Applications Center (SEDAC) Gridded Population of the World (GPW v3), 2005. [7] Hills & Goda, 1993. [8] P. Register, current workshop poster: Effects of Fragmentation Models on Atmospheric Energy Deposition. [9] Glasstone & Dolan, 1977. [10] Collins et al., 2005. [11] Toon et al., 1997. [12] Stokes et al., 2003. [13] S. Motiwala, D. Mathias, C. Mattenberger, "An Integrated Physics-Based Risk Model For Assessing the Asteroid Threat," Probabilistic Safety Assessment conference, 2015. [14] Image: S. Go, NASA ARC.